Gold(I) and Gold(III) Complexes with Anionic Oxygen Donor Ligands: Hydroxo, Oxo and Alkoxo Complexes

Maria Agostina Cinellu and Giovanni Minghetti
Dipartimento di Chimica, Università di Sassari, via Vienna 2, 07100 Sassari, Italy
E-mail: cinellu@uniss.it

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The chemistry of gold(I) and gold(III) hydroxo, oxo and alkoxo complexes containing organic co-ligands is reviewed. Due to the high reactivity of the gold-oxygen bond most of these species can be employed as useful intermediates in many important processes. Alkoxides are by far the most numerous class among these species, and both gold(I) and gold(III) complexes are known with a variety of alkoxides. The recent discovery of the catalytic activity of some gold(I) and gold(III) fluoroalkoxides has enlivened the interest towards this class of compounds leading to new applications for previously known complexes, as is the case for a gold(III) siloxo complex which has found use as a precursor for CVD, as well as for the synthesis of new alkoxo derivatives. Another well represented and well known class of compounds are the gold(I) oxo complexes $[O(AuPR_3)_3]^+$ which are the most effective aurating reagents. Gold(III) oxo complexes have been synthesized only recently and much of their chemistry is still largely to be explored. Preliminary studies suggest their potential in the transfer of oxygen atoms. Finally, some cationic gold(III) hydroxo complexes are found to display significant, and in some cases relevant, cytotoxic effects on cancer cell lines.

Gold, being the most noble of all metals, shows low affinity for binding to oxygen. Nevertheless a number of compounds with Au-O bonds have been synthesized with Au in the formal oxidation states -1, +1, +2 and +3 (1). Generally these compounds are thermally rather unstable as a consequence of a mismatch of the hard, basic oxygen ligand with the soft gold centre which causes a relatively weak Au-O linkage (2). On the other hand, weak bonds are usually highly reactive so that gold compounds containing Au-O bonds are expected to display an interesting reaction chemistry. Actually, gold-oxygen interactions are thought to be involved in the catalytic activity of gold dispersed on transition metal oxides in some relevant heterogeneous catalytic processes (3) as well as in the catalytic addition of alcohols to alkynes carried out by cationic gold(I) complexes in homogeneous phase (4). Gold(I) complexes of general formula L-Au-X, where L is a very soft neutral ligand and X is an extremely hard anionic ligand derived from an oxo- or a carboxylic acid, are relevant not only as catalytically active species (4) or catalytic precursors (5), but even in most 'auration' reactions and for gold deposition processes both from solution and from the vapour (6). Gold(III) complexes with oxygen donor ligands, such as β-diketones or alkylsiloxides, are likewise employed as precursors for chemical vapour deposition (CVD) (6). Another promising result in the field of homogeneous catalysis is the discovery that gold(I) and gold(III) alkoxo complexes promote the condensation of benzaldeyde with compounds containing an active methylene group (7). Hence it appears that gold complexes with oxygen donor ligands are of relevant technological interest. Nevertheless, this area of research is still scarcely explored.

In this paper we review organic gold complexes with OH^-, O^{2-} and OR^- (R = alkyl, aryl, silyl) ligands and give an account of the preparation and properties of each of these species.

Hydroxo Complexes

Only two organic gold(I) hydroxo complexes have been reported: [Au(MeCN)(OH)] (**1**) (8) and [Au(OH)(mpt)] (mpt = N-methylpyridine-2-thione) (**2**) (9), neither of them has been isolated in the solid state. The former is formed, together with Au(OH) (**3**), by hydrolysis of gold(I) in aqueous acetonitrile solution: the two species were identified by alkalimetric titrations and numerical analysis, with log β_2^{MeCN} being 10.7 and 10.2 respectively. For complex **2**, log β_{11} = 19.6 was obtained. The formation constants for the hydroxo species are rather high for a typical soft metal centre, therefore it appears that hydroxyde, which is rather hard and strongly basic, is a good donor for Au^I, in sharp contrast with HSAB theory (2).

Unlike gold(I), most of the gold(III) hydroxo complexes

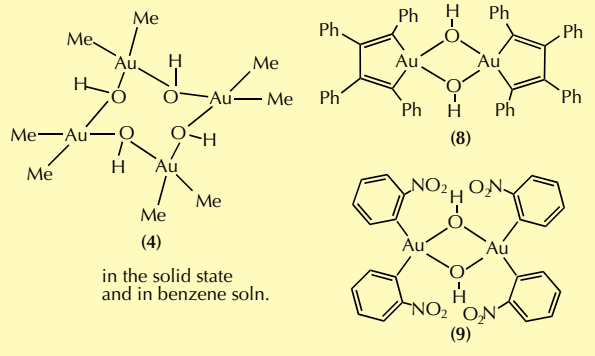
have been isolated in the solid state and their crystal stuctures determined by X-ray diffraction. Most of the reported species are polynuclear complexes with bridging hydroxides: one of the best known examples being the dimethylgold(III) hydroxide (**4**) (10) which has a dimeric structure in aqueous solution, but in the solid state or in benzene solution it is a tetramer (11). It has been prepared by treatment of dimethylgold(III) iodide with silver salts and sodium hydroxide and then precipitated by addition of nitric acid. The dimethylgold(III) aquo ion (**5**) (stable in aqueous solution) is a weak acid and transfers one proton in dilute solution over the pH range 5-7 to give the dimeric hydroxo complex (**6**) (Equation 1) (12):

$$2\,cis\text{-}[AuMe_2(OH_2)_2]^+ \rightleftharpoons [Au_2(\mu\text{-}OH)_2Me_4] + {}_2H_3O^+ \quad (1)$$
(**5**) (**6**)

$$[Au_2(\mu\text{-}OH)_2Me_4] + 20H^- \rightleftharpoons 2\,cis\text{-}[Au(OH)_2Me]^- \quad (2)$$
(**6**) (**7**)

The dimer **6** is the predominant soluble hydrolysis product: polymerization to give the water insoluble tetramer **4** occurs either in neutral aqueous solution of the hydroxide or in organic solvents. The hydroxide is also soluble in alkaline solution where the hydroxoaurate species **7** is formed (Equation 2).

Reaction of $AuCl_3$ with 1,4-dilithiotetraphenylbutadiene in ether solution yielded the hydroxo complex 1-hydroxo-2,3,4,5-tetraphenylauracyclopentadiene (**8**) (13) whose X-ray analysis revealed a dimeric structure (14). The hydroxo-bridged complex $[Au(C_6H_4NO_2\text{-}2)_2(\mu\text{-}OH)]_2$ (**9**)



Box 1 Gold(III) hydroxo complexes stabilized by C-donor ligands

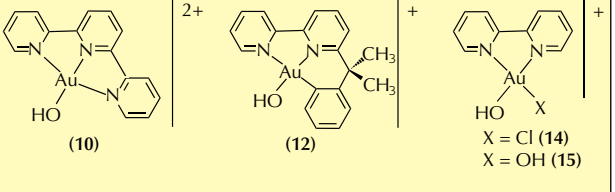
was obtained either by reaction of $Na[Au(C_6H_4NO_2\text{-}2)_2(OPh)_2]$ with traces of water in CH_2Cl_2/*n*-hexane solution or by treatment of the dichloroaurated complex with sodium hydroxide (15). The crystal structure of **9**·$2Et_2O$ shows that it is a centrosymmetric dimer, as for complex **8**, and the central Au_2O_2 ring is thus exactly planar with Au-O distances 2.073(4) and 2.075(4) Å and Au-O-Au angle 98.8(2)°; the transannular Au···Au distance is 3.150(1) Å. The coordination at gold is planar, with a mean deviation of 0.06 Å. The features of the structure include short Au-C bond distances (1.992(5) Å, 1.995(5) Å) and hydrogen bonding between the bridging OH groups and diethyl ether molecules.

Monomeric gold(III) hydroxo complexes have been described quite recently; all of them feature a polypyridine as co-ligand. The terpy derivative $[Au(terpy)(OH)][ClO_4]_2$ (**10**) (terpy = 2,2':6',2"-terpyridine) was isolated in the course of equilibrium and kinetic studies of gold(III) complexes with terpy carried out in aqueous solution (16).

$$[Au(terpy)Cl]^{2+} + H_2O \rightleftharpoons [Au(terpy)(OH)]^{3+} + Cl^- \quad (3)$$
(**11**)

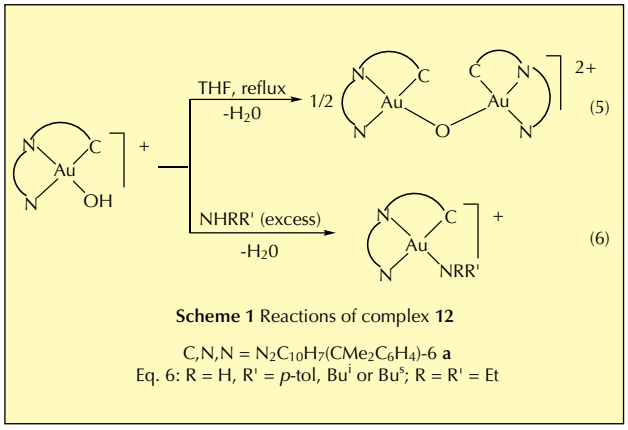
$$[Au(terpy)(O_2H)]^{3+} \rightleftharpoons [Au(terpy)(OH)]^{2+} + H^+ \quad (4)$$
(**11**) (**10**)

It has been found that the highly charged aquo complex **11**, formed according to Equation 3, behaves as a strong acid (K_a ≥ 0.8 mol dm^{-3}) and dissociates completely into the corresponding hydroxo species **10**, which can be isolated in the solid state as its perchlorate. The crystal structure of **10** has been determined by X-ray diffraction, and this is the only one determined to date for a monomeric gold(III) hydroxo complex. It consists of square planar $[Au(terpy)(OH)]^{2+}$ cations having Au-N distances of 2.009(5), 2.008(4) and 1.949(4) Å and an Au-OH distance, of 2.000(4) Å. The square planar geometry is expanded to distorted tetragonal bipyramidal by linking the two perchlorate anions with Au-O distances of 3.023(8) and 3.069(8) Å, which are intermediate between bonding and van der Waals interactions.



Box 2 Gold(III) hydroxo complexes stabilized by N-donor ligands

Treatment of the cyclometallated complex [Au(C,N,N)Cl][PF_6] (HC,N,N = 6-(1,1-dimethylbenzyl)-2,2'-bipyridine) (17) with KOH in aqueous media gave the hydroxo complex [Au(C,N,N)(OH)][PF_6] (**12**) in fairly good yields (18): it is an air stable white solid, quite soluble in water and in many organic solvents. When refluxed in anhydrous THF it condenses to give the oxo-bridged complex (**13**) (Equation 5) which, in turn, can be obtained by a different route (19) (see the oxo complexes section); the reaction can be reversed by refluxing the oxo complex in water. Complex **12** undergoes a proton exchange reaction with protic reagents to give new gold(III) complexes. For example, a series of monomeric amido complexes could easily be prepared using this route (Equation 6) (20).



Scheme 1 Reactions of complex **12**

C,N,N = $N_2C_{10}H_7(CMe_2C_6H_4)$-6 **a**
Eq. 6: R = H, R' = *p*-tol, Bu^i or Bu^s; R = R' = Et

Due to its solubility in water and good stability within a physiological buffer at 37°C, hydroxo complex **12** has been evaluated as a potential antitumour agent. Preliminary studies have shown that compound **12** exhibits relevant cytotoxic effects toward the A2780S, A2780R and SKOV3 tumour cells and has some minor effects on the CCRF-CEM/S and CCRF-CEM/R cell lines. It was also found that the interactions with the DNA double helix are weak, reversible and predominantly electrostatic in nature, suggesting that DNA is not the primary target for the cytotoxic effects of this complex (21).

Other monomeric hydroxo complexes are the two bipyridyl derivatives [Au(bipy)(OH)Cl][PF_6] (**14**) and [Au(bipy)$(OH)_2$][PF_6] (**15**) (bipy = 2,2'-bipyridyl) which have been obtained by the hydrolysis of [Au(bipy)Cl_2][PF_6] in aqueous solution (22). Partial hydrolysis to give complex **14** takes place in AcONa solution while complete hydrolysis to give complex **15** requires the presence of Ag_2O to remove the chloride ions. Both complexes undergo proton exchange in ROH (R = Me, Et, or Pr^i) solution to give the corresponding alkoxides **16** and **17** (22):

$$[Au(bipy)(OH)Cl]^+ \ (\mathbf{14}) + ROH \rightleftharpoons [Au(bipy)(OR)Cl]^+ \ (\mathbf{16}) + H_2O \quad (7)$$

$$[Au(bipy)(OH)_2]^+ \ (\mathbf{15}) + 2ROH \rightleftharpoons [Au(bipy)(OR)_2]^+ \ (\mathbf{17}) + 2H_2O \quad (8)$$

R = Me **16a**, **17a**; Et **16b**, **17d**; Pr^i **17c**

The bis amido complex [Au(bipy)$(NHC_6H_4NO_2$-4$)_2$][PF_6] has been similarly obtained by reaction of **15** with *p*-nitroaniline in acetone solution (20). Complex **15** was found to promote the stoichiometric oxidation of various amines different from *p*-nitroaniline. Azotoluene was the main organic product of the reaction with p-toluidine: other products being metallic gold and the protonated ligand [bipyH][PF_6] (20).

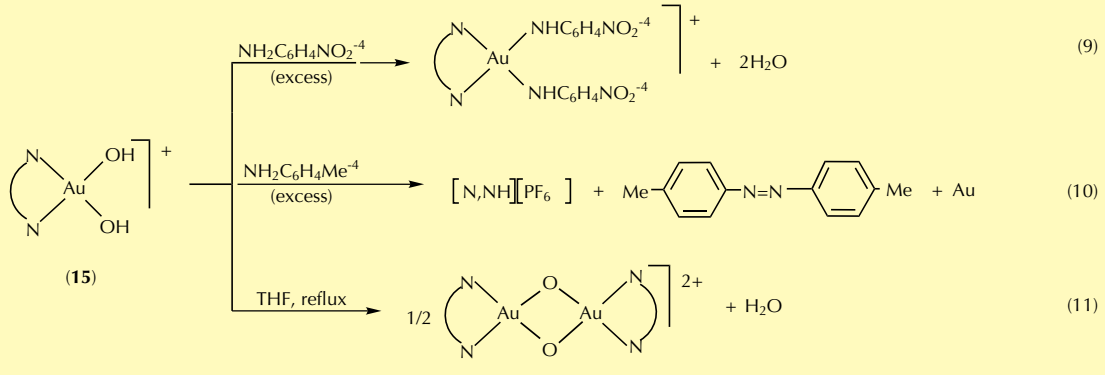
As observed for complex **12**, condensation of complex **15** also occurs in refluxing THF to give the oxo-bridged complex [Au_2(bipy)$_2$(μ-O)$_2$][PF_6]$_2$ (**18**) (22). Complex **18**, which can be most conveniently obtained by a different route (see the oxo complexes section), is converted into the hydroxo complex **15** by refluxing it in water.

The electrochemical behaviour of the hydroxo complexes **14** and **15** has been investigated using cyclic voltammetry and controlled-potential electrolysis, in two solvent systems, *ie* either 0.1 mol dm^{-3} [Et_4N][PF_6] or 0.1 mol dm^{-3} K[PF_6] in MeCN solvent, respectively, and compared with that of the dichloro precursor [Au(bipy)Cl_2][PF_6]. Both hydroxo complexes undergo an easy, irreversible one-electron reduction process. For the dichloride the first reduction process is a quasi-reversible charge transfer followed by a fast, irreversible second-order chemical reaction. Notably, substitution of Cl^- with OH^- ligands renders the electroreduction more difficult ($E_{p,c,peak\ A}$ = -0.01 V, -0.54 V, -0.88 V *vs. bis*-cyclopentadienyliron(III)/iron(II) redox couple ($Fc^{+/0}$) for dichloro, monohydroxo, and dihydroxo complex, respectively) (23).

Complex **15**, although less stable in biological media and less active with respect to the cyclometallated complex **12**, also shows important cell-killing effects with IC_{50} values falling in the micromolar range (21).

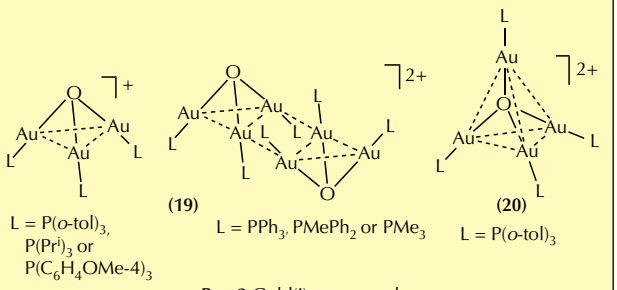
Oxo Complexes

Oxo complexes are in most cases obtained by deprotonation or by condensation of hydroxo complexes. This is not, however, the case for the best known oxo-gold complex, *ie*



Scheme 2 Reactions of complex **15**

the oxonium cation $[(AuPPh_3)_3(\mu\text{-}O)]^+$ (**19a**) which was first synthesized by Nesmeyanov and coworkers by reaction of the coordinatively unsatured cation Ph_3PAu^+ (generated *in situ* from Ph_3PAuCl and Ag^+) with water both in acidic and in basic media or by reaction of Ph_3PAuX with Ag_2O and a suitable salt in acetone solution (24).



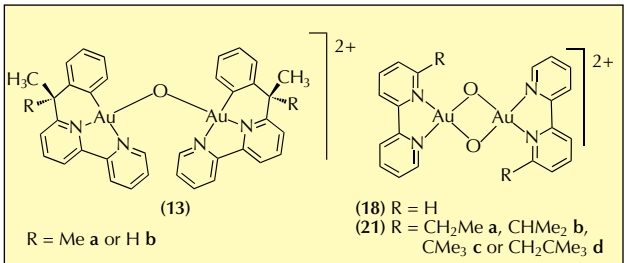
Box 3 Gold(I) oxo complexes

A number of complexes $[(AuL)_3(\mu\text{-}O)]^+$ (**19**) with a variety of phosphine ligands L have been prepared similarly (25). Trigoldoxonium salts are also produced by hydrolysis of some gold(I) complexes with nitrogen donor ligands (26). The LAu^+ cation, which is isolobal with the proton, shows such a great affinity for bonding to the strong O^{2-} Lewis base that four of these moieties can coordinate to it to form the species $[(AuL)_4(\mu\text{-}O)]^{2+}$ (**20**) (25f). Cations **19** and **20** (L = P(*o*-tol)$_3$) have been structurally characterized in various salts: depending on the bulkiness of the phosphine ligand the former exists in the solid state as a dimer with weakly interacting gold atoms (L = PPh_3 (24), L = $PMePh_2$ (25b) or L = PMe_3 (25d)) or a monomer (L = P(*o*-tol)$_3$ (25b), $P(Pr^i)_3$ (25g) or $P(C_6H_4OMe\text{-}4)_3$ (26b)); **20** shows a perfect tetrahedral core of gold atoms coordinated to the central oxygen. Notably, the average Au-O distances do not vary at all and are equal at 2.05 Å. Various aspects of the rich chemistry of the oxo-gold cations **19** have been recently reported in some reviews (27, 28, 29).

Gold(III) oxo complexes have been reported only recently: all of them are stabilized by chelating nitrogen ligands. The cyclometallated derivatives $[Au_2(C,N,N)_2(\mu\text{-}O)][X]$ (**13**) (C,N,N = $N_2C_{10}H_7(CMe_2C_6H_4)$-6 **a**, $N_2C_{10}H_7(CHMeC_6H_4)$-6 **b**; $N_2C_{10}H_8$ = 2,2'-bipy; X = PF_6 or BF_4) (19) are rare examples of metal oxo complexes with an unsupported M-O-M bridge (M = late transition metal) (29a). Complexes **13** can be prepared as the BF_4^- salts by reaction of $[Au(C,N,N)Cl][BF_4]$ with $AgBF_4$ in acetone while the PF_6^- salts are prepared by condensation of the hydroxo complexes **12**$[PF_6]$ in boiling THF. The crystal structure of **13a**$[BF_4]$ has been determined by X-ray diffraction (19). The cation displays an idealized C_2 symmetry, with the twofold axis passing through the oxygen atom and the midpoint of the Au(1)···Au(2) vector; the Au-O-Au angle is 121.3(2)° and the average Au-O distance is 1.96 Å. The distance Au(1)···Au(2) is 3.422(1) Å, too long to be considered bonding although slightly shorter than the sum of the estimated van der Waals radii.

Complex **13** can be rehydrated in boiling water to give the water-soluble hydroxide **12** whereas, surprisingly, it is quantitatively recovered from the reaction with HPF_6 in water at room temperature (18). Reaction of **13** with *p*-nitroaniline failed to give the imido complex: a 1:1 mixture of the hydroxo complex **12** and the amido complex $[Au(C,N,N)(NHC_6H_4NO_2\text{-}4)]^+$ was obtained instead (18). The oxo species $[Au_2(bipy)_2(\mu\text{-}O)_2][PF_6]_2$ (**18**) (bipy = 2,2'-bipyridine) and $[Au_2(bipy^R)_2(\mu\text{-}O)_2][X]_2$ (**21**) ($bipy^R$ = 6-alkyl-2,2'-bipyridine; R = CH_2Me **a**, $CHMe_2$ **b**, CMe_3 **c** or CH_2CMe_3 **d**; X = BF_4 or PF_6) have two gold atoms bridged by two oxygen, each gold is coordinated to two nitrogen atoms of a bipyridine ligand (22, 30). Complex **18** can be prepared by reaction of $[Au(bipy)Cl_2][PF_6]$ with an aqueous solution of KOH in acetonitrile or by condensation of the hydroxo complex **15** in boiling THF. Complexes **21** have been obtained either as BF_4^- salts by reaction of the adducts $[Au(bipy^R]Cl_3]$ with $AgBF_4$ in acetone or as PF_6^- salts by reaction of the adducts with AcONa and excess KPF_6 in $MeCN/H_2O$. The structure in the solid state of *trans*-$[Au_2(bipy^R)_2(\mu\text{-}O)_2][PF_6]_2$ (**21d**) has been determined by X-ray diffraction (30). The dinuclear cation displays crystallographic inversion symmetry and the central Au_2O_2 ring is thus exactly planar with a rather short transannular Au···Au distance 3.017(1) Å. The average Au-O bond length, 1.97 Å, is similar to that found for the monooxobridged complex **13** and can be compared with the 1.93(2) Å Au-O distance, observed in polymeric gold(III) oxide, involving an oxygen atom that bridges two gold atoms (31).

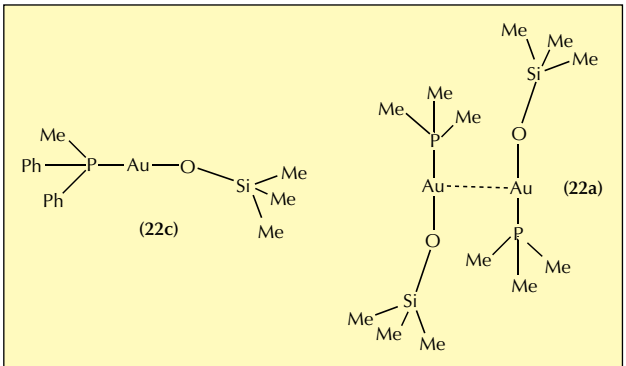
The hydroxo complexes $[Au(bipy^R)(OH)_2]^+$, postulated as intermediates in the formation of **21**, have not been isolated; nevertheless, in all the mass spectra a weak peak was found corresponding to this species. Unchanged **21** are quantitatively recovered from the reaction with aqueous solutions of HX (X = BF_4 or PF_6): neither dihydroxo complexes similar to those observed in the vapour phase, nor hydroxo bridged dimers are obtained (30). Reaction with primary arylamines gave similar results as those observed in the case of the hydroxo complex **15**; for example, the reaction with *p*-toluidine afforded azotoluene, the protonated ligand and elemental gold (32). Complexes **21** were tested in oxygen transfer reactions; for example, from the reaction with PPh_3, $OPPh_3$ was obtained together with the gold(I) complex $[Au(PPh_3)_2][X]$ and free $bipy^R$ ($bipy^R$ = 6-alkyl-2,2'-bipyridine) (18).



Box 4 Gold(III) oxo complexes

Alkoxo Complexes

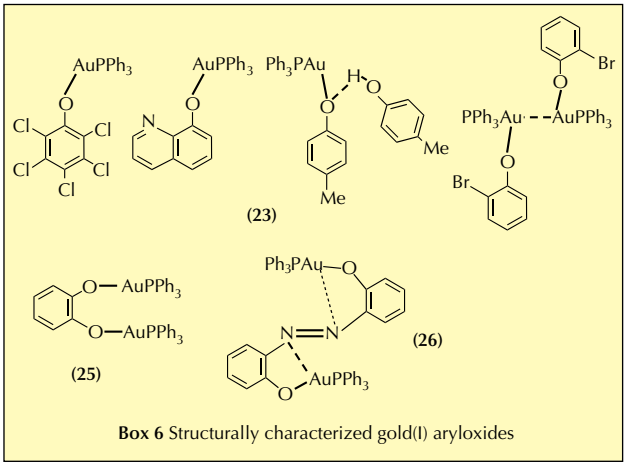
A number of monomeric gold(I) alkoxo complexes have been reported and the crystal structure determined in most cases. All complexes are stabilized by a tertiary phosphine ligand. Early examples are represented by the siloxo complexes [(R_3P)AuOSiMe$_3$] (**22**) (R = Me **a**, Ph **b**) (33); and the crystal structures of **22a** (34a) and **22c** (PR_3 = $PMePh_2$) (34b) have been determined recently by X-ray diffraction. Complex **22c** is a monomer in the solid state whereas **22a** is a dimer with Au···Au distance of 3.376(1) Å, indicating a weak ineraction between the gold centres.



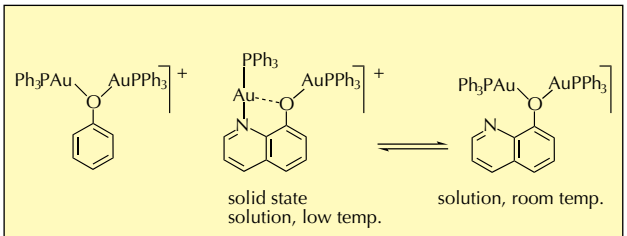
Box 5 Structurally characterized gold(I) silyloxides

Aryloxy derivatives are known for several phenols (35) including 8-hydroxyquinoline (36) and 2,2'-dihydroxyazobenzene (37); all complexes have been prepared by reaction of the oxonium salt **19** with the phenol or with the potassium phenolate. The crystal structures of most of them have been ascertained by X-ray diffraction analysis: both mononuclear, ArOAuPPh$_3$ (**23**) (Ar = mono- or pentasubstituted- phenyl (35a-d) or 8-hydroxyquinoline (36a)), and dinuclear species are found.

The latter are of different types: *ie* [ArO(AuPR$_3$)$_2$]$^+$ (**24**) (Ar = phenyl or 8-hydroxyquinoline, R = Ph, 2-MeC_6H_4, Et (**36b**)), [ArO_2(AuPPh$_3$)$_2$] (**25**) (ArO_2H_2 = pyrocatechol (35e)) and [Ar$_2O_2$(AuPPh$_3$)$_2$] (**26**) (Ar$_2O_2H_2$ = 2,2'-dihydroxyazobenzene (37)). Interestingly, for the phenoxo and the quinoline-8-oxo derivatives both mononuclear and dinuclear structure of type **24** have been found. The dinuclear phenoxide differs from dinuclear quinoline-8-oxo complex in the coordination mode of the two AuPPh$_3$ groups which are both coordinated to the oxygen atom in the former, while in the latter, at least in the solid state, one is bound to the oxygen (Au-O 2.033(6) Å) and the second to the nitrogen atom (Au-N 2.101(6) Å): in addition, a short interaction between the nitrogen bound gold and the oxygen atom is also present (Au···O 2.575(6) Å). Nevertheless, the other coordination mode is present in solution, where dissociation of the [AuPPh$_3$]$^+$ unit from the pyridine donor and shift towards the oxygen atom occurs at room temperature: evidence is provided by the $^{31}P\{^1H\}$ spectrum which shows equivalence of the phosphine ligands (36b). Both intra- and intermolecular Au···Au interactions are present in some cases (35c, 35e).



Box 6 Structurally characterized gold(I) aryloxides



Box 7 Coordination modes of the dinuclear complexes **24**

Some aspects of the reactivity of the aryloxo complexes (35c) are also reported; for example, complexes ArOAuPPh$_3$ (**23**) undergo proton exchange with PhC_2H or with $CH_2(CN)_2$ to give the corresponding organogold derivatives.

$$\underset{(\mathbf{23})}{ArOAuPPh_3} + PhC{\equiv}CH \longrightarrow ArOH + PhC{\equiv}C\text{-}AuPPh_3 \qquad (12)$$

$$\underset{(\mathbf{28})}{2ArOPPh_3} + CH_2(CN)_2 \longrightarrow 2ArOH + (CN)_2C(AuPPh_3)_2 \qquad (13)$$

A small number of gold(I) alkyloxides are known and their reactivity is of special interest. The sterically bulky Bu^{t}OAuPPh$_3$ (**27**) and the fluoroalkoxides ROAuPR'$_3$ (R = $CH(CF_3)_2$, CH_2CF_3; R' = Ph, Cy) (**28**), which are readily prepared from the chlorides by simple metathetical reactions, are able to abstract hydrogen atoms from transition metal hydrides to give Au(I) heterodinuclear complexes, having Au-M bonds, with the liberation of the corresponding alcohols (38, 39). Complexes **28** can abstract protons from various organic substances such as malononitrile, methylcyanoacetate and even acetone to give the corresponding organogold compounds and the free alcohol (40). By reaction with an equimolar amount of phenol in benzene they are converted into the phenoxogold(I) complexes, thus indicating the higher stability of the latter derivatives with respect to the alkoxides (40).

$$3Bu^tOAuPPh_3 + ReH_5(PMe_2Ph)_3 \longrightarrow 3Bu^tOH + (PhMe_2P)_3ReH_2(auPPh_3)_3 \quad \textbf{(14)}$$
(**27**)

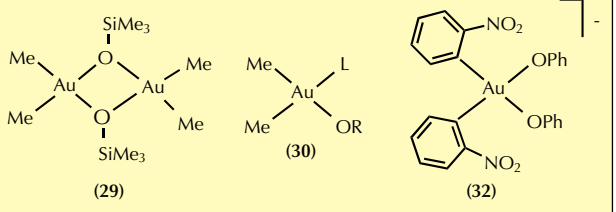
$$(CF_3)_2CHOAuPR_3 + MH \longrightarrow (CF_3)_2CHOH + M\text{-}AuPR_3 \quad \textbf{(15)}$$
(**28**)

R = Ph, Cy; MH = $CoH(CO)_4$, $ReH(CO)_5$, $MoHCp(CO)_3$, $WHCp(CO)_3$, $WHCp(CO)_2(PMe_3)$

Catalytic amounts of complexes **28** are found to promote Knöevenagel condensation reactions between benzaldehyde and the active methylene compounds $CH_2(X)(Y)$ which are able to react with **28** as indicated in Equation 16 (7). The C-bonded gold enolates likewise formed are the active catalysts for the condensation reaction. Other interesting reactions, carried out by both the alkoxo $(CF_3)_2CHOAuL$ (**28**) and the phenoxo PhOAuL (23')(L = PPh_3, PCy_3, PMe_3, PMe_2Ph) complexes, are the selective ring opening of thiiranes to give 2-(alkoxy- or -aryloxy)ethylsulfanylgold(I) complexes under ambient conditions (41) and the C-Si bond cleavage of trihalomethyltrimethylsilane to give trihalomethylgold complexes $Au(CX_3)L$ and the corresponding silyl ether Me_3SiOR (42). Ring opening takes place at the less hindered C-S bond of the thiirane. The proposed mechanism of the reaction involves a S_N2 type *trans* addition of the alkoxogold(I) complex toward thiiranes.

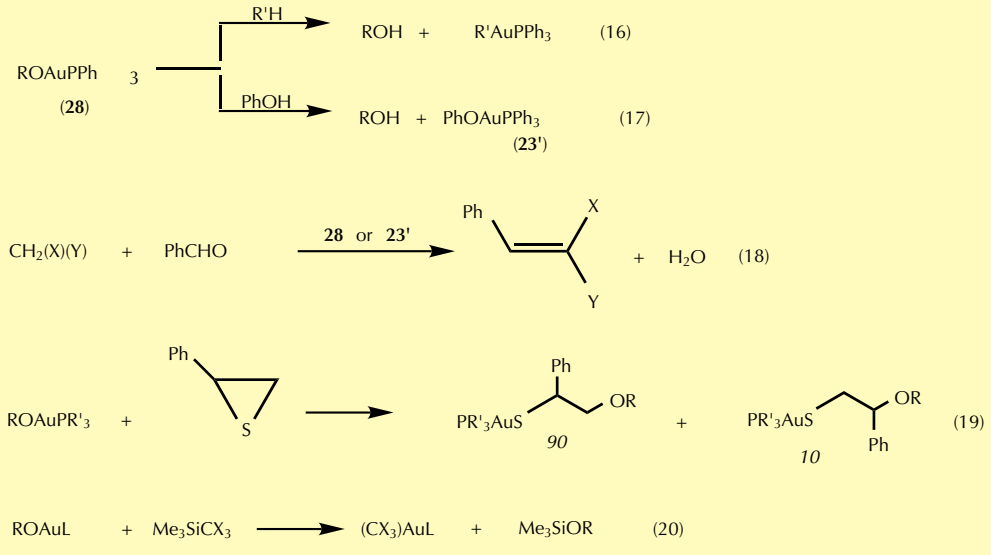
Gold(III) alkoxo complexes, stabilized by a variety of ancillary ligands, are known with the same alkoxo ligands which have been found to give stable gold(I) complexes. Even in this case an early example is the siloxane compound $[Me_2AuOSiMe_3]_2$ (**29**) which features a four-membered ring structure with silyloxide bridges between the square planar gold centres (43). This complex has found recent application as precursor for chemical vapour deposition (CVD) (44).

Thermally stable aryloxo and fluoroalkoxo complexes having the general formula *cis*-$[AuMe_2(OR)(PPh_3)]$ (**30**) (R = Ph **a**, *p*-tol **b**, CH_2CF_3 **c**, $CH(CF_3)_2$ **d**) have been synthesized by metathesis of *cis*-dimethyliodo (triphenylphosphine)gold(III) with potassium alkoxides in THF (45). The crystal structure of the phenoxo derivative, determined by X-ray diffraction analysis, features a typical square-planar configuration with normal bond distances (Au-O 2.09(1) Å) and angles, no unusual intra- and intermolecular contacts are observed. Incorporation of one mole of phenol to give a *cis*-dimethylphenoxo(phenol)(triphenylphosphine)gold(III) complex takes place after recrystallization of the complex in the presence of phenol. The phenol is linked with the



30: R = CH_2CF_3, $CH(CF_3)_2$, Ph;L = PPh_3, $PCy3$, $PMePh_2$, PMe_2Ph, PMe_3, PEt_3

Box 8 Stable gold(III) alkoxides stabilized by C- donor ligands



Scheme 3 Reactions of complexes **28** and **23'**

Eqs. 16 and 17: R = CH_2CF_3, $CH(CF_3)_2$; R' = $CH(CN)C(O)Me$, $CH(CN)_2$, CH_2COMe
Eqs. 18: X = CN, Y = CO_2Me, CO_2Et; X = H, Y = COPh; X = Y = CN
Eqs. 19: R = $CH(CF_3)_2$, R' = Ph, R' = Ph, Cy, Me
Eqs. 20: $CH(CF_3)_2$, Ph; L = PPh_3, PCy_3, PMe_2Ph, PMe_3; X = Cl, F

phenoxo group by hydrogen bonding; the two groups do not mutually exchange on the NMR time scale. Complexes *cis*-[$AuMe_2(OR)(PR'_3)$] (**30**) (R = CH_2CF_3, $CH(CF_3)_2$, Ph; R' = Ph, Cy) give rise to the same reactions as do the corresponding gold(I) complexes. Thus, reaction with metal hydrides (MH = $CoH(CO)_4$, $MnH(CO)_5$, $MoHCp(CO)_3$, $WHCp(CO)_3$, $WHCp(CO)_2(PMe_3)$) proceed to liberate the free alcohol and give R_3PAu-M accompanied by evolution of an equimolar amount of ethane (39); reaction with active methylene compounds, in non-polar solvents, results in hydrogen abstraction to give the free alcohol and the corresponding organogold derivatives (45). Although less active than the corresponding gold(I) alkoxides, fluoroalkoxides *cis*-[$AuMe_2(OR)(PPh_3)$] (R = CH_2CF_3, $CH(CF_3)_2$) can act as catalysts for the Knöevenagel condensation reaction (7).

At variance with analogous alkoxogold(I) complexes, only the aryloxides *cis*-[$AuMe_2(OPh)L$] (**30a**) (L = $PMePh_2$, PMe_2Ph, PMe_3, PEt_3) are capable of cleaving the C-Si bond of Me_3SiCF_3 (42). A large steric effect of the ancillary phosphine is observed in the case of gold(III), thus suggesting that the gold centre is also taking part in the rate determining step of the C-Si bond cleavage reaction. A four-centre concerted intermediate has been proposed.

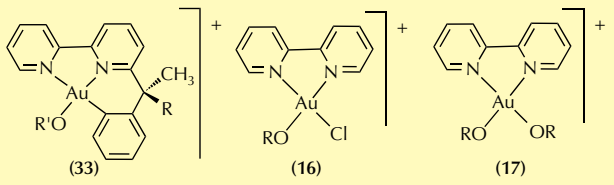
Alkoxo complexes *cis*-[$AuMe_2(OR)(PPh_3)$] (**31**)(R = Me **a**, Et **b**, Pri **c**), although not isolated, have been prepared in situ from cis-[$AuMe_2I(PPh_3)$] and sodium alkoxide in alcohol or by alcoholysis of *cis*-[$AuMe_2\{CH_2CH{=}CHMe\}(PPh_3)$] in methanol; the highly reactive alkoxides readily insert carbon monoxide, which can be bubbled in the solution, to give alkoxocarbonyl complexes *cis*-[$AuMe_2(COOR)(PPh_3)$] (46).

Similarly, the alkoxogold(III) intermediate *cis*-[$AuMe_2\{OCH(Ph)CH_2CH{=}CH_2\}(PPh_3)$] (**31'**), formed from the insertion of benzaldehyde into the Au-allyl bond in *cis*-[$AuMe_2\{CH_2CH{=}CH_2\}(PPh_3)$], has been detected by ^1H NMR; **31'** can be obtained by alcoholysis of the methallylgold(III) complex *cis*-[$AuMe_2\{CH_2C(Me){=}CH_2\}(PPh_3)$] with the homoallylalcohol, $PhCH(OH)CH_2CH{=}CH_2$ (47). The alkoxo intermediate **35'** reacts with active methylene compounds to give free homoallyl alcohol and C-bonded gold(III) enolates.

The anionic diphenoxide $Na[Au(C_6H_4NO_2\text{-}2)_2(OPh)_2]$ (**32**), obtained by metathesis of the chloride $Me_4N[Au(C_6H_4NO_2\text{-}2)_2Cl_2]$ with NaOPh, is quite stable in the solid state but in dichloromethane solution it was found to react with traces of water to give the neutral dimeric hydroxo complex **9** (15).

Stable alkoxogold(III) complexes have been isolated very recently with 6-benzyl-2,2'-bipyridines and 2,2'-bipyridine as co-ligands. The cyclometallated derivatives $[Au(N,N,C)(OR)][PF_6]$ (**33**) (C,N,N = $N_2C_{10}H_7(CMe_2C_6H_4)$-6, $N_2C_{10}H_7(CHMeC_6H_4)$-6; $N_2C_{10}H_8$ = 2,2'-bipy; R = Me **a**, Et **b**, Pr^i **c**, $CH_2C_6H_4NO_2$-3 **d**, Ph **e**, *p*-tol **f**) have been prepared according to different routes which depend both on the C,N,N and on the alkoxo ligand (18, 48).

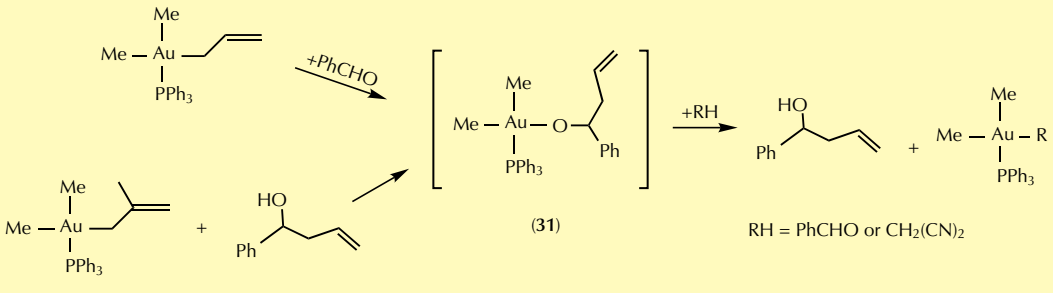
For example, with the dimethylbenzyl substituted ligand both methoxo and ethoxo derivatives can be prepared by metathesis of the chloride $[Au(N,N,C)Cl][PF_6]$ with NaOR (R = Me, Et) in ROH, whereas with the methylbenzyl substituted bipy the same alkoxides can be achieved only by proton exchange of the acetato complex $[Au(N,N,C)(OAc)][PF_6]$ with ROH, since the benzylic C-H bond of the substituent, in the chloride complex, is activated by the strong base NaOR (48).



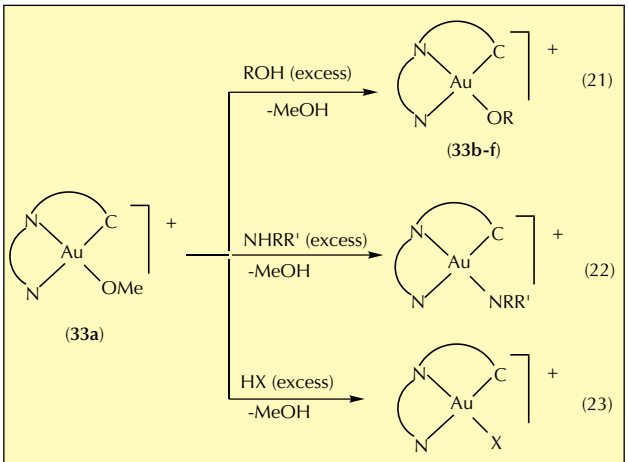
33 R = H, Me; R' = Me, Et, Pr^i, $CH_2C_6H_4NO_2^{-3}$, Ph,*p*-tol;
16 R = Me, Et; **17** R = Me, Et, Pr^i

Box 9 Gold(III) alkoxo complexes stabilized by N-donor lligands

All the other alkoxides, **33b-f**, are readily prepared using proton exchange between the methoxo complex and ROH under mild conditions (Equation 21) (18). The methoxo derivatives are the best starting materials also for the synthesis of a number of complexes of general formula $[Au(N,N,C)X][PF_6]$, where X is a C-, N- or S-donor anionic ligand, by proton exchange with HX (Equations 22-23) (48,



Scheme 4 Formation and reactivity of the alkoxo intermediate **31**



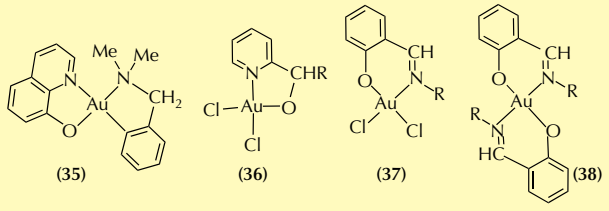
Scheme 5 Reactions of complex **33a**

Eq. 21: R = Me,Et, Pr^i, $Ch_2C_6H_4NO_2$-3, Ph, *p*-tol
Eq. 22: R = H, R' = $C_6H_4NO_2$-4, *p*-tol, Bui, Bus; R = R' = Et
Eq. 23: X = C_2Ph, S-C_6H_4Me-4

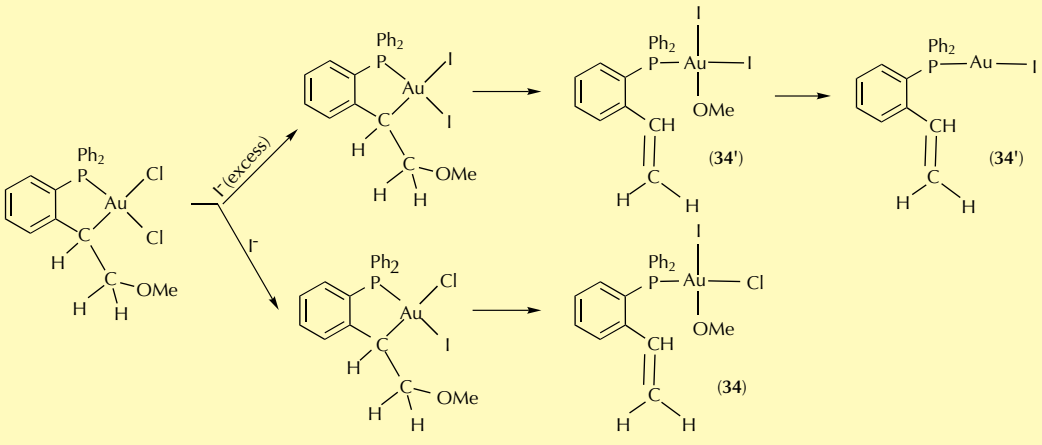
20). The bipy derivatives [Au(bipy)(OR)Cl][PF_6] (**16**) (R = Me, Et) and [Au(bipy)(OR)$_2$][PF_6] (**17**) (R = Me **a**, Et **b**, Pr^i **c**) are the only examples of gold alkoxides which are stabilized by nitrogen donor ligands only (22). While complexes **16** are exclusively prepared by proton exchange reaction of the hydroxide **14** with ROH (Equation 7), complexes **17** can be obtained either by this route, from complex **15** (Equation 8) or from the diacetato derivative [Au(bipy)(OAc)$_2$][PF_6], or by metathesis of the dichloro [Au(bipy)Cl_2][PF_6] with NaOR (R = Me, Et) in ROH solution (22). The crystal structure of the dimethoxo complex **17a** has been determined by X-ray diffraction analysis (22). The gold atom displays square-planar coordination with normal bond distances and angles. The Au-O distances, 1.971(4) and 1.960(6) Å, are slightly shorter than those found in other alkoxogold complexes.

The methoxo complex [Au(sp)(OMe)(Cl)I] (**34**) (sp = diphenyl-2-styrylphosphine), possessing fairly good stability, has been fully characterized in solution (49). It is the final product of a rearrangement induced by the substitution of a chloride with an iodide in the cyclometallated complex [Au(sp-OMe)Cl_2] (sp-OMe = 2-CH-(CH_2OMe)$C_6H_4PPh_2$). At variance with **34** the analogous methoxo intermediate [Au(sp)(OMe)I_2] (**34'**), although detected in solution, undergoes spontaneous reduction to [Au(sp)I] and, presumably, IOMe which further decomposes to HI and HCH=O (49). Finally, a number of gold(III) complexes with chelating N,O ligands have been reported.

In these ligands activation of the O-H bond to give the alkoxogold derivative is made easier by the coordination of a heterocyclic nitrogen atom, as in the case of the 8-hydroxyquinoline derivative [Au(dmp)(N,O)][BF_4] (**35**) (dmp = 2-(dimethylaminomethyl)phenyl) (50) and of the 2-pyridylmethanol and 2-(2-pyridyl)ethanol derivatives [Au(N,O)Cl_2] (**36a, 36b**) (51), or of an iminic nitrogen, as in the case of the Schiff bases derivatives [Au(N,O)Cl_2] (**37**) and [Au(N,O)$_2$][AuX_4] (**38**) (N,OH = 2-HOC_6H_4CH=NR; R = Me **a**, Et **b**, Pr^i **c**, Bu^n **d**, $CH_2C_6H_5$ **e**, C_6H_{11} **f**; X = Cl, Br) (51). Some of the [Au(N,O)Cl_2] derivatives, namely **36a, 37a** and **37b**, have been tested for cytotoxic properties against various human tumor cell lines (52). All of them show significant cytotoxic effects. In particular, the salycilaldiminato derivatives induced tumor cell growth inhibitory effects comparable to or even greater than cisplatin (52b). Their binding to DNA is tight but reversible and results into a modest stabilization of the double helix (52c).



Box 10 Gold(III) alkoxo complexes with chelating N,O ligands



Scheme 6 Formation and reactivity of methoxo intermediates **34** and **34'**

About the Authors

Professor Giovanni Minghetti, after graduating (Laurea) in Industrial Chemistry and teaching Inorganic Chemistry at the University of Milan, moved in 1980 to the University of Sassari (Italy) as full Professor of General and Inorganic Chemistry. His research work is concerned with the synthesis and reactivity of coordination and organometallic derivatives of late transition metals, and in particular with platinum, palladium and gold. In the last ten years he has been involved mainly in the chemistry of heterocyclic nitrogen ligands such as pyrazoles, pyridines and 2,2'-bipyridines. Particular interest has been devoted to the intramolecular activation of C-H bonds. He is author of about 130 papers mostly in international journals and over 90 communications.

Maria Agostina Cinellu works as a Senior Researcher in the Department of Chemistry at the University of Sassari. Her research interests include the synthesis and reactivity of inorganic and organometallic derivatives of d^8 metal ions stabilized by nitrogen donor ligands. She has recently been involved in investigating the chemistry of gold(III) complexes with anionic oxygen donor ligands

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